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ABSTRACT

A spherical reaction member for a three-axis attitude control is described and compared with the common one-axis flywheel system. Special problems are considered; such as, control of the space vehicle with the spherical reaction member, torquing the sphere, supporting it by a bearing, and measuring its speed.

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1. INTRODUCTION

The principal requirement which a control system of a space vehicle has to fulfill is to create, to compensate, or to counteract an angular momentum of the space vehicle. This angular momentum may possess any direction in space; it depends on disturbing torques the space vehicle has experienced and on reorientation requirements.

A very attractive method to exert control torques to a space vehicle is given by the inertial reaction torque principle. One of the commonly known solutions to apply this principle is to provide three separate flywheels with motors in a mutually orthogonal arrangement[1,2]. Such a combination of three one-axis systems seems to be a straight forward approach from the viewpoint of three-axis control.

In case of the use of three single flywheels, the total angular momentum necessary for the spatial attitude control of the vehicle will be separated into the three components in the directions of the three mutually orthogonal flywheel axes. However, if the directions of the three body-fixed flywheel axes change, due to a reorientation of the space vehicle, another separation of the total angular momentum according to the reoriented flywheel axes has to take place. The result is a coupling effect between the three flywheel control systems of the space vehicle, actually connected with any attitude change, and a behavior which is undesirable from the viewpoint of power requirements.

2. THE SPHERICAL CONTROL MOTOR

The foregoing considerations reveal that a direct control of the total angular momentum without having to separate it into components is most preferable, not only to avoid coupling effects but also to reduce the number of the flywheels from three to one.

The solution to this problem of direct control of the angular momentum vector is the spherical control motor, which may be considered as a three-axis flywheel motor system. The sphere, which should be hollow from the viewpoint of a high moment of inertia to weight ratio, has to be mounted in a bearing which gives full freedom of rotation. Three mutually orthogonal arranged torquers, which are fixed to the bearing or to the space vehicle, replace the three motors of the one-axis flywheel system.

Due to the ideal symmetry characteristics of the sphere, the control of each body axis is independent of the other two axes, if coupling effects of the sensing and torque excitation system can be disregarded. In the following, the main problem areas of the spherical control motor will be investigated:

1. the requirements for stability of the control motions,

2. the speed measurement on the sphere,

3. the suspension methods for the spherical flywheel,

4. the torquing methods of the sphere.

2.1 Principal Requirements for Stability of the Control Motions

Assuming that it will be possible to obtain mutually independent control of the torques with respect to the three main axes of the vehicle, it will be sufficient to investigate the control behavior of one axis.

In this case the control characteristics are the same as of a single flywheel reaction type system described in Reference 2.

The following derivation for a linear control system with constant ratio of the input signal to the output torque is applicable to any type of motor which can be described by linear differential equations.

The equation of torque equilibrium about the axis to be controlled gives

$$I_{sv}\ddot{\phi} + I_f\ddot{\alpha} = 0 \tag{1}$$

with

I_{sv} = moment of inertia of space vehicle about axis to be controlled

I_f = moment of inertia of spherical flywheel

ϕ = angular displacement of space vehicle,) measured in a
input signal) space direction
) fixed system

α = angular displacement of flywheel)

Dots above variables denote time derivatives.

The input signal ϕ should be differentiated to provide proper damping of the control mode. Sampling type or digital type differentiating methods are preferable to the commonly used analog methods in form of RC networks or to rate gyros since unusually low control frequencies are desirable from the viewpoint of low power needs. Thus, the input signal ϕ and its derivative $\dot{\phi}$ will cause, after proper amplification, the necessary motor torque and the compensation of the inherent damping of the motor, which might be modified by a feedback of the angular rate $\dot{\alpha} - \dot{\phi}$:

$$a_o \phi + a_1 \dot{\phi} = I_f \ddot{\alpha} + e\,(\dot{\alpha} - \dot{\phi}) \qquad (2)$$

Equations (1) and (2) yield the characteristic equations

$$s^2 = 0 \qquad (3a)$$

and $$s^2 + s \left[e\left(\frac{1}{I_{sv}} + \frac{1}{I_f}\right) + \frac{a_1}{I_{sv}} \right] + \frac{a_o}{I_{sv}} = 0 \qquad (3b)$$

The two poles at s = 0 allow for two initial conditions with respect to α and $\dot{\alpha}$. The initial displacement α of the flywheel is of no concern, whereas the initial value of the flywheel speed $\dot{\alpha}$ should be zero* in order to have symmetrical starting conditions for the operating range of the control system. Thus, the stability of the flywheel control system is sufficiently described by Equation (3b).

Equation (3b) indicates that the system behaves like a damped pendulum with the undamped natural frequency

$$f_c = \frac{1}{2\pi}\sqrt{\frac{a_o}{I_{sv}}} \qquad (4a)$$

and the relative damping ratio

$$\zeta = \frac{1}{2}\left[e\left(\frac{1}{I_{sv}} + \frac{1}{I_f}\right) + \frac{a_1}{I_{sv}} \right]\sqrt{\frac{I_{sv}}{a_o}} \qquad (4b)$$

The use of non-linear control characteristics such as amplitude dependent gain factors or a properly selected response zone will improve the overall efficiency of the control circuit. The former method results in reduced power requirements, while use of a dead zone permits conditional stability without special damping requirements. Further, no control power will be necessary when passing through the dead zone.

*A steady state condition ($\ddot{\phi} = \ddot{\alpha} = \dot{\phi} = 0$) may arrive at relatively high values of $\dot{\alpha}$ due to an initial angular impulse of the space vehicle or a one-directional perturbation torque. In order to avoid in the described linear system a large attitude angle ϕ required to satisfy Equation (2), a feedback of the motorspeed is essential to compensate for the emf of the motor. In this case, where e = 0, damping can only be attained by a sufficiently high a_1 gain factor.

2.2 Speed Measurements on the Sphere

If conditional stability of the control loop due to nonlinearities does not give sufficient dynamic stability, damping of the control loop can, in addition to the inherent damping of the sphere due to losses, be provided by a signal proportional to the speed of the sphere as mentioned in paragraph 2.1. Such signals may be derived by one of the following methods:

a. Bolometer type pickups as shown in Figure 1: On a sphere rotating in air, an air flow exists along the surface which can be used for cooling of a heating element. Its temperature difference measured by thermocouples on both ends in a bridge circuit produces a signal which is close to a linear function of the speed of the sphere.

b. Inductive types of pickups as shown in Figure 2 on a smooth sphere: The excitation a.c. flux ϕ_e along the path a-b-d-e does not induce any voltage in coil c as long as the sphere does not rotate around the axis normal to the magnetic flux. Such a rotation, however, will distort the magnetic flux distribution due to eddy currents in the sphere. The magnitude of voltage induced due to the unsymmetrical flux distribution in coil c of the middle core will be close to a linear function of the speed of the sphere and its phase with respect to the excitation voltage allows a discrimination of the speed direction.

This can be shown by the following consideration, which is valid when a modest speed of the sphere and thus a negligible current skin effect prevail. Then the magnetic flux ϕ_e produced by the excitation coils is constant and produces an emf in the rotating sphere proportional to its speed. Since the sphere is an electrical conductor, this induced emf causes a current density and ampere turns again proportional to the speed of the sphere and directed in such a way that a magnetic cross flux ϕ_c is created which induces a proportional voltage in coil c.

c. Magnetic or optic pickups measuring the time interval of pulses produced by a pattern marked on the sphere. Both methods do not look very promising since relatively complex measuring and speed direction discriminating electronics have to be used.

2.3 Suspension Methods for the Spherical Flywheel

An air bearing consisting of two or more spherical calotte bearings as shown in Figure 3 provides an almost torque-free support and centering for the sphere. Since the flywheel control methods will only be applied during flight periods in which very low angular and translational accelerations of the space vehicle occur, the air pressure and the consumption of circulating air can be kept very low. The result is a low power consumption for the air bearing and low aerodynamic torques even at a high speed of the sphere.

The air-surrounded sphere will produce windage losses which are approximately proportional to the square of the speed. A nonlinear damping results for the control motions; however, the magnitude is very small due to low viscosity of the air.

Another possibility to support the sphere is by means of magnetic suspension as indicated in Figure 4. A set of four or more stabilizing coils with magnetic cores for the magnetic flux allow the proper centering of the sphere, which has to be made from magnetic material. As shown in Figure 4B, control circuits for the stabilizing currents may be used which are controlled from the inductance changes of the stabilizing coils due to air gap variations.

It will be shown later that it is possible to combine the magnetic suspension system with an a-c torquing system (Figure 5).

The magnetic flux needed for suspension causes hysteresis and eddy current losses in the rotating sphere; the first of which is proportional to, the second, a square function of the speed of the sphere. From the viewpoint of desirably small power requirements, both losses should be kept small; e.g., by using a steel powder, sintered sphere. The low angular and translational accelerations expected during the flight phase in which flywheel attitude control is feasible, allows low density magnetic fields for bearing constraint. This fact also contributes towards keeping the losses small.

A special type of magnetic bearing is the superconductive magnetic bearing. Below certain temperatures close to absolute zero, some conducting materials do not have any electrical resistance. The same stabilizing arrangement as mentioned above, of stabilizing coils and sphere, can be applied with minimum power losses if the stabilizing coils and the sphere or its surface are made of superconductive materials such as niobium, tin or its alloys[3].

The dynamic balancing of the sphere, especially of a hollow one, presents a problem. Since the surface of the sphere should remain smooth from the viewpoint of windage losses, balancing would be achieved by removing material from the inside of the sphere. Thus, the sphere should be assembled of two halfspheres, which unfortunately aggravates the machining tolerance problem and produces a magnetic and electric dissymmetry of the sphere.

The magnetic bearing with low pressure or vacuum conditions is almost insensitive to small outside cavities from balancing the sphere. Considering also the low losses of the magnetic suspension method, its application is most promising for the subject purpose.

2.4 Torquing Methods for the Sphere About Three Mutually Perpendicular Axes

The main problem in providing torquers is given by the fact that the sphere may assume any position with respect to the torquers. Thus, the sphere should either be used with a smooth surface or with pronounced markings (either by magnetizing or by milling of recessions) of a relatively high number in order to avoid preferred axes of rotation which results in an undesirable coupling effect of the control axes.

One method to torque the sphere in the demanded manner is by means of air nozzles. The disadvantage of this method is that the required torques can only be produced very inefficiently and thus, require considerable power. Pockets in the surface of the sphere of course will increase the turbine effect, but, they also will increase the windage losses.

The most promising torquing method is by electrical means (see Figure 3). Two or more phase a.c. torquers can produce torques due to hysteresis and eddy current effects on the magnetic sphere. Disregarding the losses in the stator of the motor, the following relationship exists for an induction, eddy current or hysteresis type motor:

$$N_1 = N_{2el} + N_{2mech} = N_1\sigma + N_1\ (1 - \sigma)$$

with N_1 = input power

N_{2el} = losses in rotor (5)

N_{2mech} = mechanical power output of rotor

σ = slip of rotor

If a certain torque T at a defined speed n is demanded, the corresponding output power is (with n_s = synchronous speed)

$$N_{2mech} = T.n = Tn_s\ (1 - \sigma) \tag{6}$$

or with Equation (5) it will be

$$N_1 = Tn_s \tag{7}$$

$$N_{2el} = N_1\sigma = Tn_s\sigma \tag{8}$$

Equation (7) says that the input power of the motor will be proportional to the selected synchronous speed of the motor. This means that, for a particular maximum torque requirement and storable angular impulse, the synchronous speed should be selected as low as possible to avoid unnecessary power demands and, as Equation (8) shows, unnecessary losses.

For control purposes it will be advantageous if the motor produces a torque as a function of the control signal and independent of the actual speed of the rotor. The hysteresis motor fulfills this requirement best; however, for practical reasons only a combination of the hysteresis and the induction or eddy current type motor can be realized. A search for materials must be undertaken which will allow a favorable combination of torques from the hysteresis and the eddy current effects. The application of sintered or baked magnetic material (ferrites) with high hysteresis and low eddy current losses for the outer layer of the sphere seems to be very desirable. Figure 5 shows a cross section through such a sphere which is hollow and uses plastic or metallic material to support the sintered magnetic hull and, if necessary, to contribute to the required amount of inertia of the sphere.

It may be mentioned here that a combination of the magnetic torquer and the magnetic suspension is possible, which reduces the number of control coils. The magnetic torquer needs at least one phase which has an almost constant excitation. This same phase can be used as bearing coil for the magnetic suspension as indicated in Figure 5.

A special magnetic torquing method is given by applying the superconductivity principle. In this case, it is not possible to produce torques on the smooth surface of a sphere because the superconductive surface acts like a perfect magnetic shield. Thus, the surface has to be marked as symmetrically as possible by spherical recessions, which form a kind of poles. In order to obtain a high number of such poles with a highly symmetrical distribution, the patterns of regular polyhedrons, such as a icosahedron or a dodecahedron, will be used directly or with additional poles which further subdivide the polyhedral surfaces.

The advantage of the superconductive principle is that no losses occur in or on the surface of the sphere and that practically no operating power is necessary to maintain any speed of the sphere, which is in a very low vacuum due to the superconductive temperature.

The greatest difficulty and disadvantage of the superconductivity principle is foreseen in the complexity of the torque control system. Due to the impossibility of having a symmetrical pattern of the poles in all great circles of a sphere, each individual torquer coil will need its own position sensing and current control system.

2.5 Characteristics of the Spherical Flywheel and the System of Three One-Axis Flywheels

The parameters which influence the selection of an actuation system are too manifold to establish clear dividing lines for the feasibility of each actuation method.

Thus, some of the common and some of the distinguishing characteristics of the spherical and the one-axis flywheel systems will be considered in this paragraph and the most important comparison viewpoints valid for the selection of either system will be given. For a specific attitude control system only a thorough analytical investigation can reveal the proper actuation system.

Those requirements for an attitude control system with flywheel actuation which depend on the size of the space vehicle will be considered first.

Table I presents the growth factors of characteristic data for the design of flywheel actuation systems. The comparison of these growth factors shows that the actuation torque will increase with the same power as the perturbation and reorientation control torques. However, the response of the control system will be more sluggish with an increase in size of the space vehicle, because the ratio of the maximum motor torque to the moment of inertia of the space vehicle is inversely proportional to the square of the size factor.

TABLE I
GROWTH FACTORS OF CHARACTERISTIC DATA FOR ACTUATION SYSTEM

Data for Design of Flywheel Actuation System	Growth with Size Factor d	Remarks and Assumptions
power from solar energy	d^2	changes inversely with the square of the distance from the sun
from nuclear sources	d^3	
heat radiation area	d^2	
weight of space vehicle, flywheel and reaction motor	d^3	
maximum torque of flywheel motor	d^3	constant specific motor design factors assumed
moment of inertia of space vehicle and flywheel	d^5	
perturbation torques e.g., solar radiation	d^3	
gravitational (dumbbell) effects	d^5	inversely proportional to third power of distance from center of the earth
internal moving parts	can be limited to d^3 or less	acceleration requirements to be reduced
reorientation control torques	can be limited to d^3 or less	acceleration requirements to be reduced

TABLE I (CONTINUED)
GROWTH FACTORS OF CHARACTERISTIC DATA FOR ACTUATION SYSTEM

Data for Design of Flywheel Actuation System	Growth with Size Factor d	Remarks and Assumptions
initial perturbation from separation process	d^5	constant initial angular velocity assumed, reduction possible
maximum angular velocity ω_{av} of space vehicle during control mode	d^{-1}	assumed allowance
power requirement for flywheel motor	d^2	for assumed ω_{sv} prop. d^{-1}
	d^3	if ω_{sv} would be constant
storable max angular impulse on flywheel	d^4 d^5	if ω_{fmax} prop. d^{-1} if ω_{fmax} does not change
power requirements of all space vehicle components	expected to grow with at least d^3	depends on space vehicle missions

An unfavorable fact is that the energy drawn from solar converters shows the smallest growth factor. Thus, it may become desirable to reduce the relative power requirements of the actuation system in favor of other power consumers even when an increase of the relative actuation torque is required.

The torques obtainable on a spherical flywheel are comparatively lower than the torques obtainable with the separate motor of the one-axis flywheel; additionally the separate motor can be designed with a better overall efficiency or with lower losses. Thus, the advantages of the spherical reaction type motor are seen mainly in the field of space vehicles, up to some thousands pounds weight, such as instrumented satellites and small manned space vehicles, whereas the one-axis flywheel system will preferably be used for large space vehicles.

Viewpoints for the proper selection of the moment of inertia of the flywheel, the motor size, and for suitable power and weight allowances are given in Reference 4. They have to be applied to the design of the two competing flywheel systems. The distinguishing facts of the spherical against the one-axis flywheel system mentioned above in addition to some other important ones will reveal the best solution for a particular control problem.

Such additional distinguishing facts of the two types of flywheel systems are:

(a) Space Vehicle Reorientation: the spherical flywheel system gives practically no coupling effect of the three control axes;
the three-axis flywheel system needs more power for angular impulse transfer unless a space direction stabilized base is available for the three flywheels.

(b) Electrical Power for Flywheel Motor: the torque motors for the spherical flywheel have to use ac; their overall efficiency is smaller than the corresponding efficiency of the motors of the one-axis flywheel system, which can be designed for ac or dc.

(c) Torque Level of Flywheel Motor: the torque motors for the spherical flywheel cannot reach the torque level of single axis ac or dc motors.

(d) Flywheel Bearing: 1 Magnetic suspension is considerably more complex and consumes more power if applied to the one-axis flywheel system especially for higher torque levels than to the spherical flywheel.
2 Air bearing support is simpler for the spherical flywheel; it requires circulatory air-feeding system with pump; in general the power requirements are higher for larger flywheels and higher flywheel speeds than with magnetic suspension.
3 The lifetime of any ballbearing is very limited even under moderate vacuum conditions. (See also para. 2.3 of this report).

(e) Control Computer: Straight forward three axis control through the spherical flywheel motor; no first-order coupling effects if space vehicle has to be reoriented. The one-axis flywheel system will show coupling effects of the three axes, which in certain configurations of stored angular momentum will demand complex decoupling terms in computer.

(f) Using Active Missile Components for the Flywheel Mass: No feasible method can be seen to replace the spherical flywheel mass by active missile components. One-axis flywheels, allowing the use of sliprings, can accommodate batteries and other electrical equipment.

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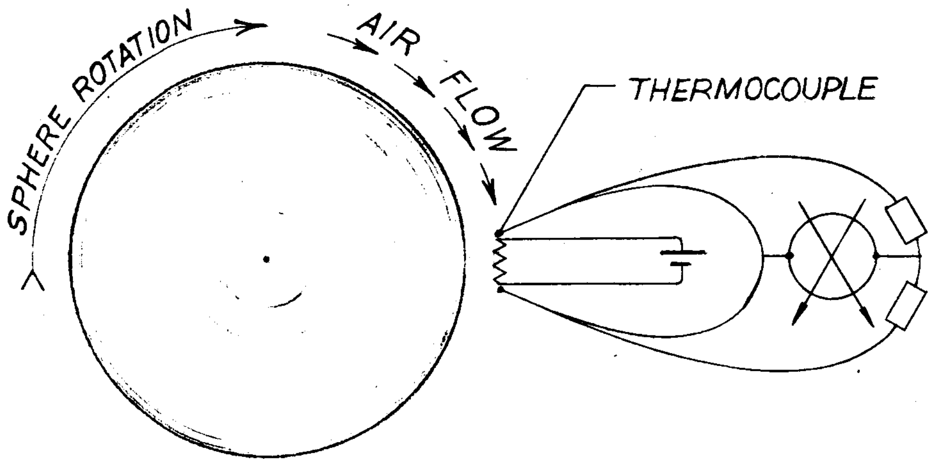
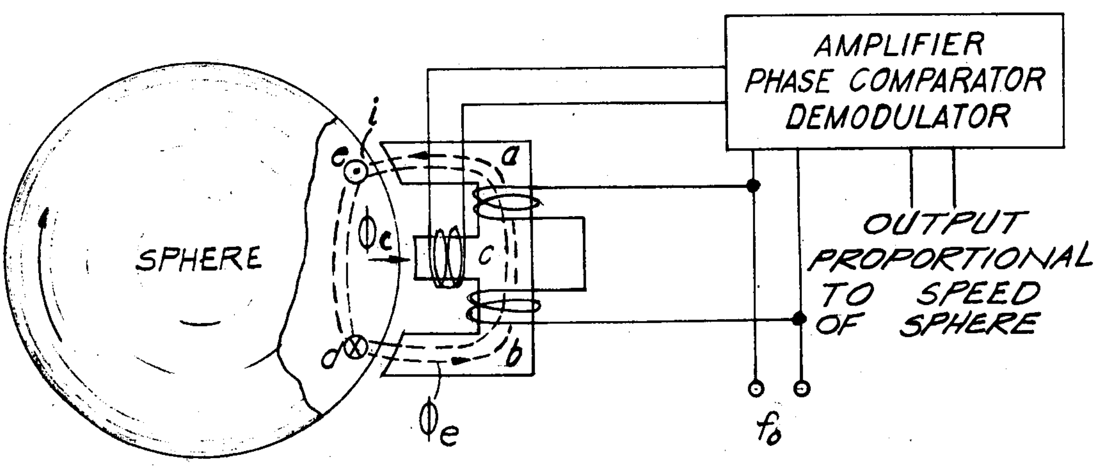
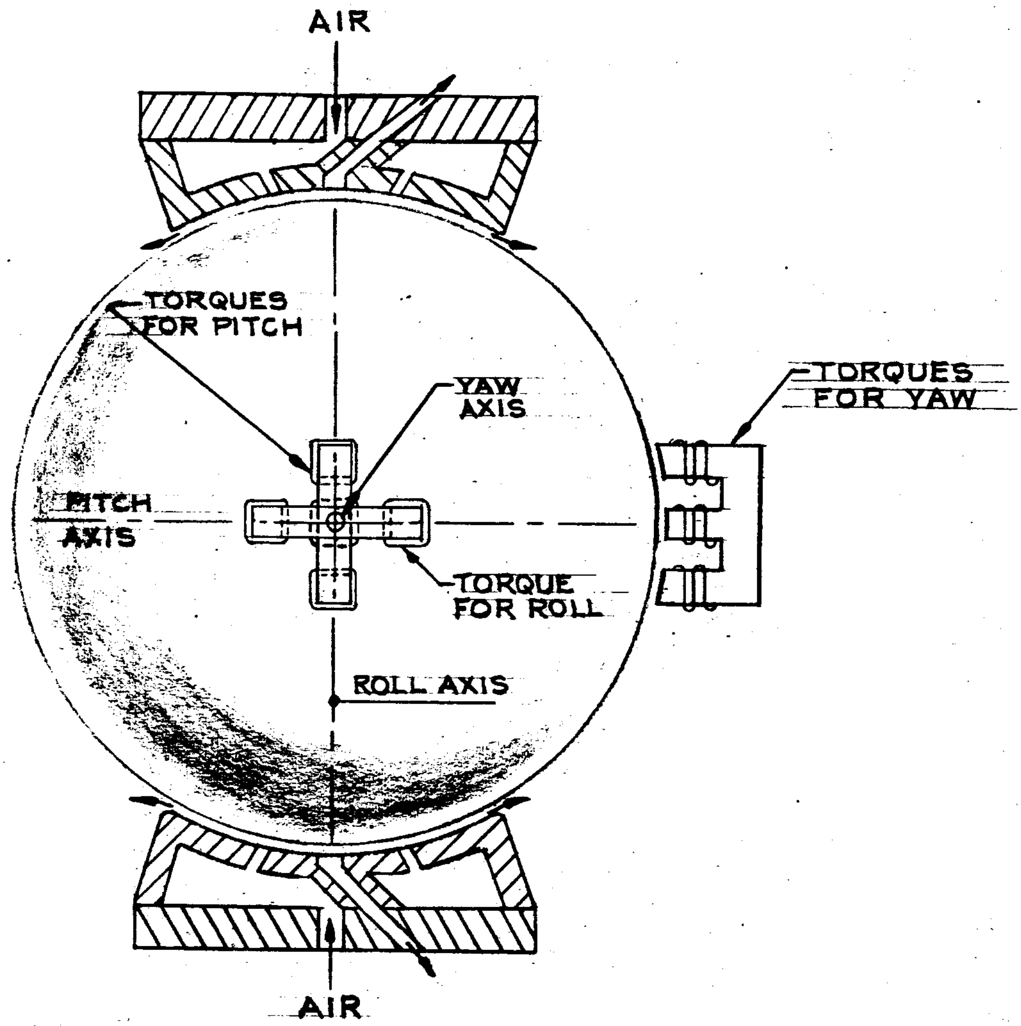


BOLOMETER TYPE SPEED
MEASUREMENT
FIG. 1



FLUX AND CURRENT DIRECTIONS
ARE SHOWN FOR A FROZEN TIME

INDUCTIVE TYPE SPEED MEASUREMENT
FIG. 2



ELECTROMOTIVE TORQUING OF SPHERICAL CONTROL MOTOR WITH AIR BEARING SUPPORT

FIG 3

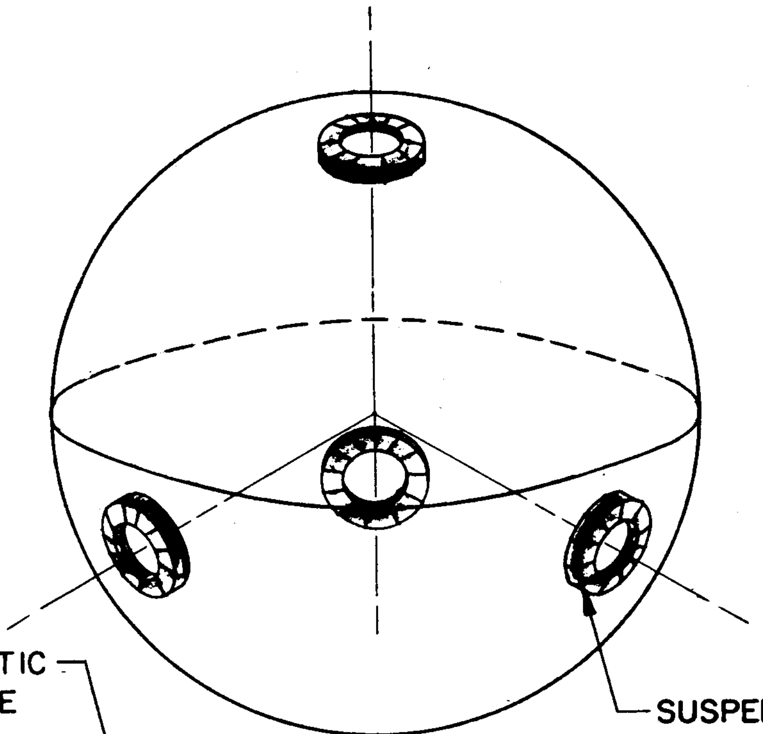


FIG. 4A

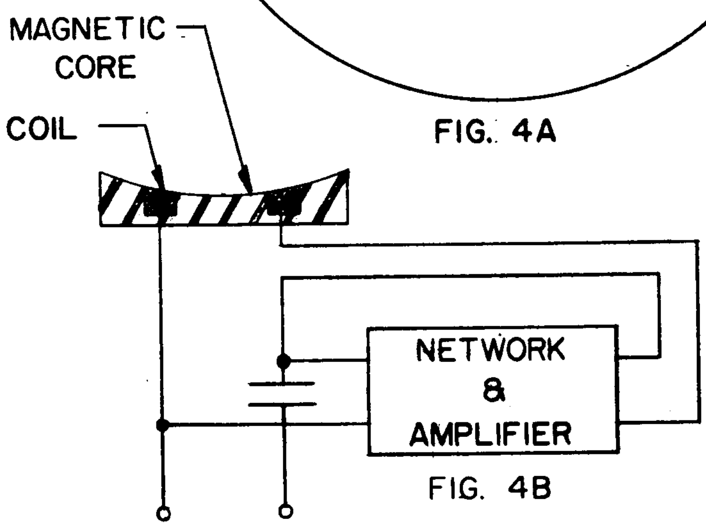
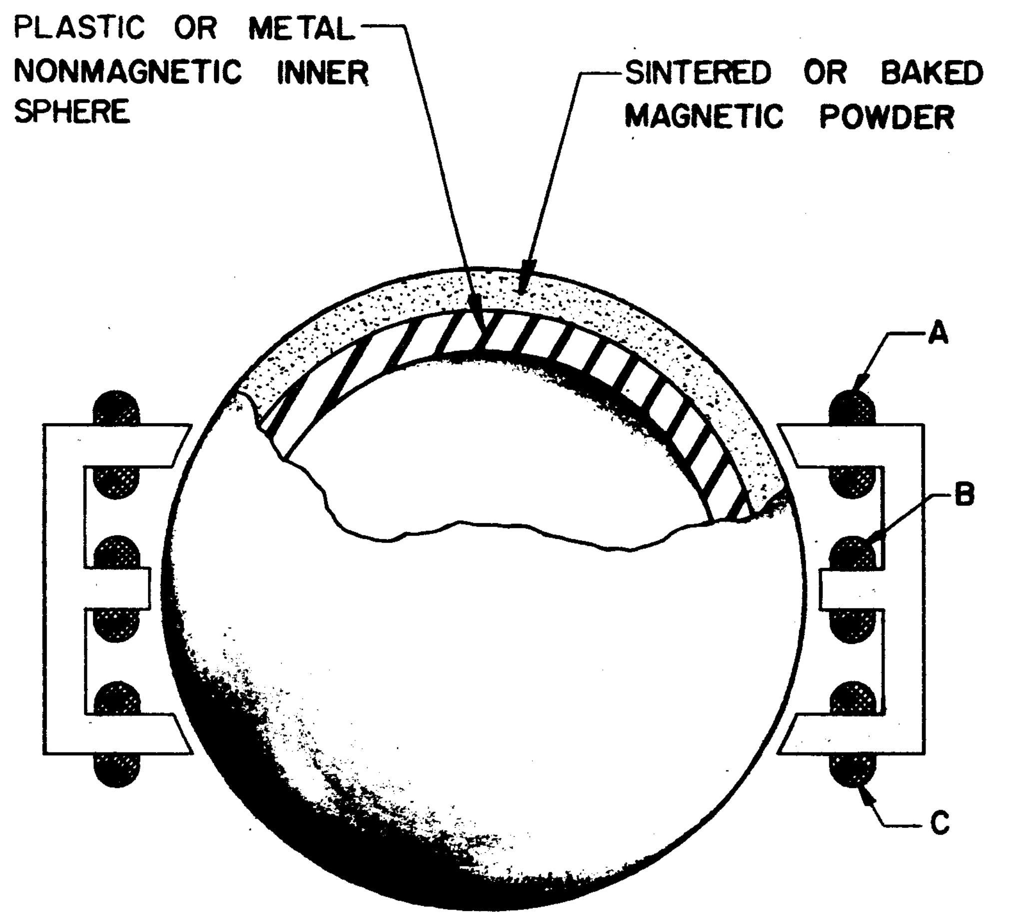


FIG. 4B

MAGNETIC BEARING SUSPENSION WITH A MINIMUM OF 4 COILS

FIG. 4



- COIL "A" AND "C" FOR TORQUE CONTROL.
- COIL "B" FOR TORQUE EXCITATION AND MAGNETIC SUSPENSION.

COMBINED MAGNETIC BEARING AND TORQUING SYSTEM ON HOLLOW SPHERE

FIG. 5